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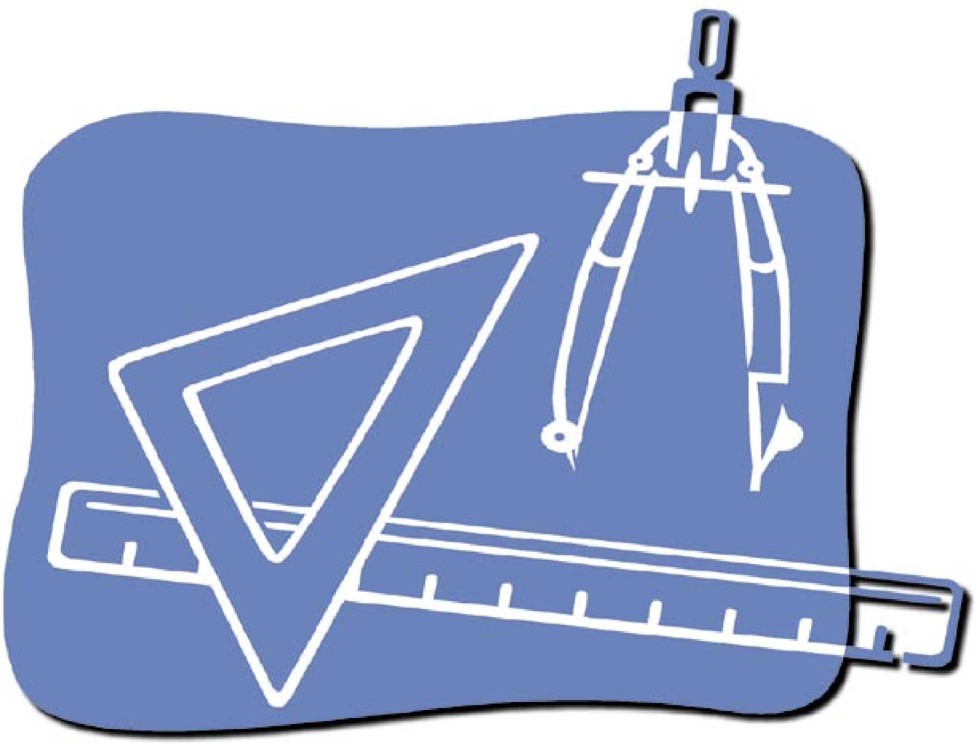
Building America Research Benchmark Definition, Version 3.1, Updated July 14, 2004



Robert Hendron
National Renewable Energy Laboratory

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Building America Research Benchmark Definition

Version 3.1, Updated July 14, 2004

To track progress toward aggressive multi-year whole-house energy savings goals of 40-70% and onsite power production of up to 30%, the U.S. Department of Energy (DOE) Residential Buildings Program and the National Renewable Energy Laboratory (NREL) developed the Building America Research Benchmark in consultation with the Building America industry teams. The Benchmark is generally consistent with mid-1990s standard practice, as reflected in the Home Energy Rating System (HERS) Technical Guidelines (RESNET 2002), with additional definitions that allow the analyst to evaluate all residential end-uses, an extension of the traditional HERS rating approach that focuses on space conditioning and hot water. A series of user profiles, intended to represent the behavior of a "standard" set of occupants, was created for use in conjunction with the Benchmark.

Benchmark House Specifications

The following sections summarize the definition of the Benchmark, Version 3.1. A more comprehensive description of the Benchmark can be found in the NREL technical report addressing systems-based performance analysis of residential buildings (Hendron 2004), along with definitions of other important Building America reference houses (Builder Standard Practice and Regional Standard Practice) and guidance for using hourly simulation tools to compare an energy efficient prototype house to the various base case houses. NREL and other Building America partners also developed a series of tools, including spreadsheets with detailed hourly energy usage and load profiles, to help analysts apply the Benchmark quickly and in a consistent manner. These tools can be found on the Building America web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html).

Any element of the Benchmark definition that is not specifically addressed in the following sections is assumed to be the same as the Prototype house. Because the definition is intended to be software-neutral, certain elements of the Benchmark cannot be modeled directly using every common simulation tool. The full Building America Performance Analysis Procedures (Hendron 2004) include application notes addressing some practical implementation issues that may be encountered when simulating the Benchmark using DOE-2.2 or EnergyGauge.

Building Envelope

All building envelope components (including walls, windows, foundation, roof, and floors) for the Benchmark shall be consistent with the HERS Reference Home as defined by NASEO/RESNET in the "National Home Energy Rating Technical Guidelines," dated September 19, 1999 (RESNET 2002). These requirements are summarized below, along with a few minor clarifications and additional requirements. References to U-values in the 1993 Model Energy Code (MEC) have been updated to 2003 International Energy Conservation Code (IECC), because the corresponding U-values are identical and the IECC is more readily available (ICC 2003).

The Benchmark envelope specifications are as follows:

- The same shape and size as the Prototype.
- The same area of surfaces bounding conditioned space as the Prototype, with the exception of the attic (this shall be insulated at the attic floor and have a ventilation area of 1 ft^2 per 300 ft^2 ceiling area, regardless of the Prototype attic design).
- The same foundation type (slab, crawl space, or basement) as the Prototype.
- The same basement wall construction type as the Prototype (e.g., masonry, wood frame, other).
- No sunrooms.
- No horizontal fenestration, defined as skylights, or light pipes oriented less than 45 degrees from a horizontal plane.
- Window area (A_F) determined by Equation 1 for detached homes and by Equation 2 for attached homes:

Equation 1: $$A_F = 0.18 \times A_{FL} \times F_A$$

Equation 2: $$A_F = 0.18 \times A_{FL} \times F_A \times F$$

where

A_F = total window area

A_{FL} = total floor area, including basement

F_A = (exposed thermal boundary wall area)/(total thermal boundary wall area)

F = (total thermal boundary wall area)/(total thermal boundary wall area + common wall area) or 0.56, whichever is greater,

and where

total thermal boundary wall is any wall that separates directly or indirectly conditioned space from unconditioned space or ambient conditions, including all insulated basement walls, but not including unvented crawl space walls;

exposed thermal boundary wall is any thermal boundary wall not in contact with soil; and

common wall area is the total area of walls adjacent to another conditioned living unit, including basement and directly or indirectly conditioned crawl space walls.

- Window area assigned according to the following requirements:
  - Distributed equally in each of the four cardinal directions (north, south, east, and west); for orientation neutrality in attached homes; this may require windows located in common walls.
  - Vertical distribution on each façade shall be in proportion to the fraction of thermal boundary wall area on the façade associated with each floor, including the basement. This may require window wells for below-grade basement walls if the Prototype includes a walk-out basement. If the modeling tool does not allow windows in basement walls,

then the entire window area shall be distributed in proportion to the external wall area of the façade for above-grade floors.

- Thermal conductance of all thermal boundary elements equal to the requirements, expressed as U and U_o values, of Paragraph 502.2 of the 2003 IECC (ICC 2003), as summarized below. Unless otherwise specified, these U-values are for entire assemblies, including sheathing, framing, finishes, and so on.
    - Total wall assembly U_o from Figure 1 (excerpted from ICC 2003).
    - U-value (U_w) for the opaque fraction of exterior walls from Table 1 or 2, as appropriate.
    - The U-value for windows is calculated using Equation 3 or is equal to 1.3, whichever is less:

Equation 3: $$U_F = [(U_o \times A_o)-(U_w \times A_w)-8]/A_F$$

where

U_F = required average U-value of the windows, including framing and sash

U_o = average U-value requirement for walls from Figure 1

A_o = gross exposed wall area, not including basement or crawl space walls, of the Prototype

U_w = U-value from Table 1 or 2

A_w = net opaque wall area, calculated as A_o - A_F - 40

A_F = area of windows.

Note: For walls of attached homes, the U-value in Equation 3 is calculated by using the total window area calculated as A_F and the actual area of walls that experience heat loss or gain. Areas of common walls that separate homes are not included in A_o.

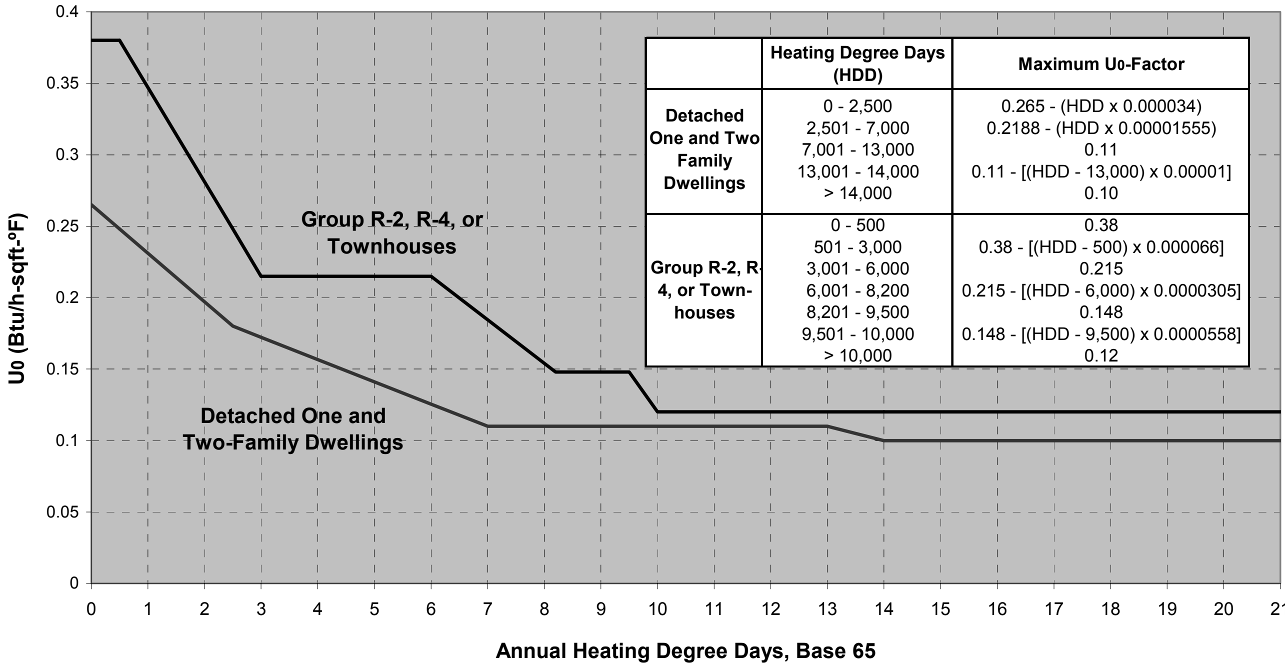


Figure 1. Wall assembly U-value (U_0) (excerpted from ICC 2003)

Table 1. Opaque Wall U-Values (U_w) for Detached Homes

Annual Heating Degree Days Base 65 (HDD65) from Nearest Location Listed in Chapter 9 of ASHRAE Standard 90.2 or NREL's *Solar Radiation Data Manual*[1]	U_w Air to Air, Includes Framing
>13000	0.038
9000-12999	0.046
6500-8999	0.052
4500-6499	0.058
3500-4499	0.064
2600-3499	0.076
<2600	0.085

[1] See *Solar Radiation Data Manual for Buildings* (or the "Blue Book") published by the National Renewable Energy Laboratory (NREL 1995) (http://rredc.nrel.gov/solar/old_data/nsrdb/bluebook/).

Table 2. Opaque Wall U-values (U_w) for Attached Homes

Heading Degree Days Base 65 (HDD65) from Nearest Location Listed in Chapter 9 of ASHRAE Standard 90.2, or NREL's *Solar Radiation Data Manual*	**U_w Air to Air Includes Framing**
>9000	0.064
7100-8999	0.076
3000-7099	0.085
2800-2999	0.100
2600-2799	0.120
<2600	0.140

- U-value of an insulated floor above a vented crawl space or other unconditioned space shall be as specified in Figure 2 (excerpted from ICC 2003).
- U-value of insulated walls in an unvented crawl space shall be as specified in Figure 3 (excerpted from ICC 2003). This U-value represents the combined effect of wall components and the surface air film, but it does not include adjacent soil.
- U-value of insulated basement walls shall be as specified in Figure 4 (excerpted from ICC 2003), and the insulation shall be located on the interior surface of the walls. This U-value represents the basement wall assembly, including the surface air film, but it does not include ground effects.
- R-value and depth of slab-edge insulation for slab-on-grade construction shall be as specified in Figure 5 (excerpted from ICC 2003). This R-value is for rigid foam insulation and does not include ground effects.
- U-value of insulated roof/ceiling shall be as specified in Figure 6 (excerpted from ICC 2003). If the Prototype includes an attic, the Benchmark shall have an unconditioned attic with insulation at the attic floor.

- Solar heat gain coefficient (SHGC) equal to 0.581 for window assemblies, including the effects of framing and sash.
- No external shading at any time from roof projections, awnings, adjacent buildings, trees, etc.; basic architectural features such as attached garages and enclosed porches shall be included in the Benchmark model, but it shall not include window shading effects from these features.
- No self-shading shall be modeled for the Benchmark.
- Total area of opaque exterior doors is equal to 40 ft^2, facing north, with door U-value equal to 0.20 (air to air).
- Solar absorptivity is equal to 0.50 for opaque areas of exterior walls and 0.75 for opaque areas of roofs.
- Total emittance of exterior walls and roofs is equal to 0.90.
- The above-grade exterior walls shall be light-frame 2x4 or 2x6 wood construction with sufficient insulation to achieve the correct overall U-value. The framing factors in Table 3 are representative of typical construction practices and shall be used as inputs for the Benchmark model.
- Interior partition walls shall be light-frame (2x4) wood construction.
- Masonry floor slabs shall have 80% of floor area covered by R-2 carpet and pad and 20% of floor area directly exposed to room air.

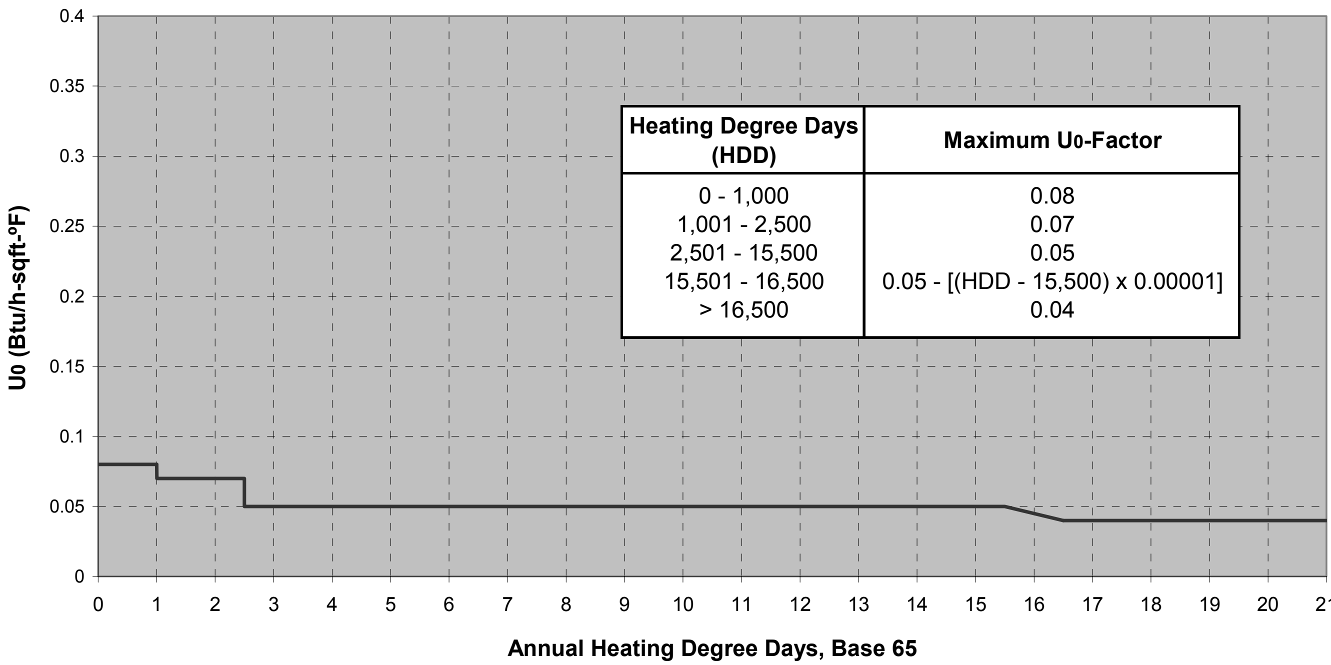


Figure 2. U-value of floor over unconditioned space (excerpted from ICC 2003)

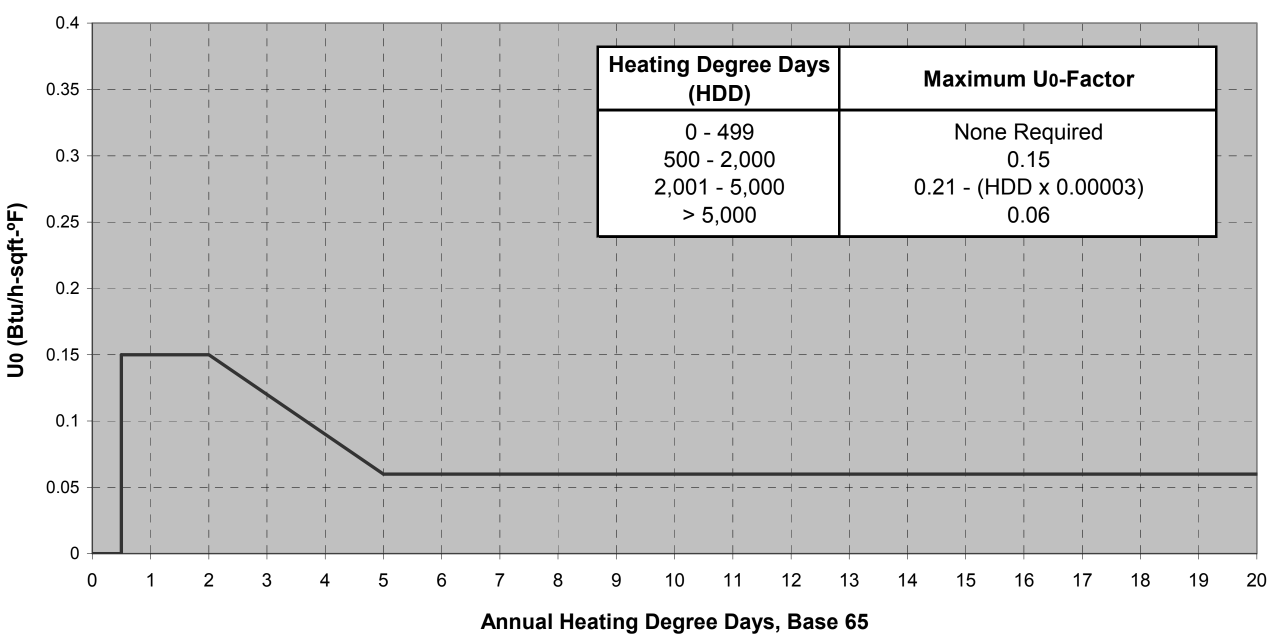
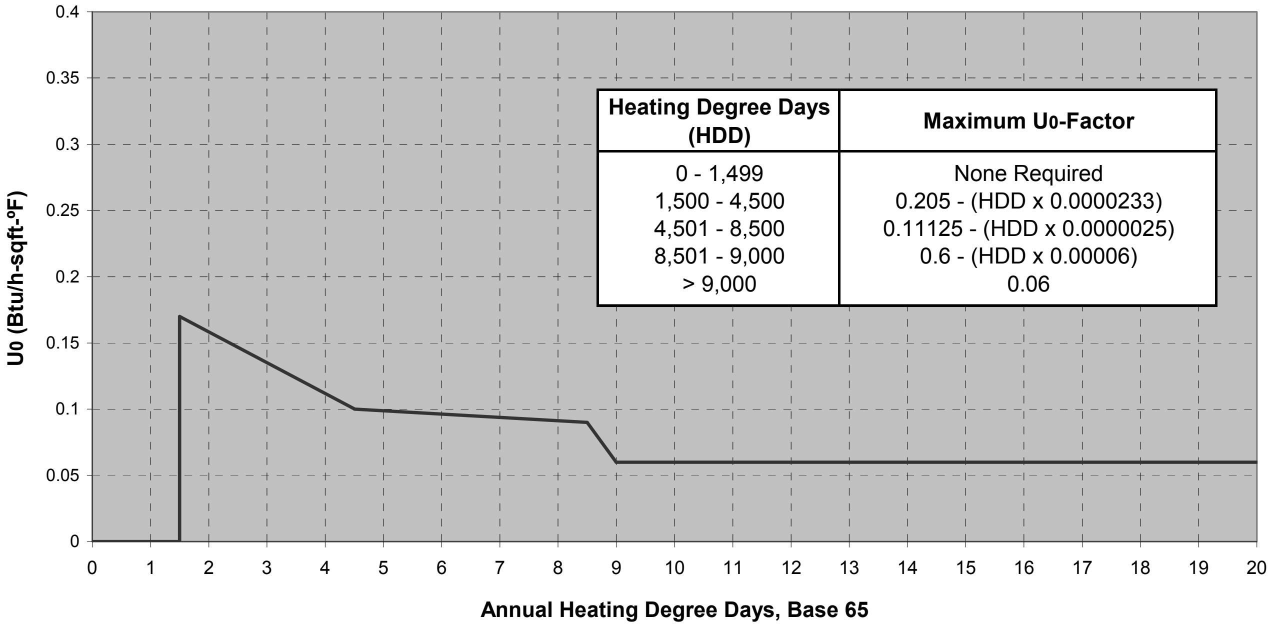
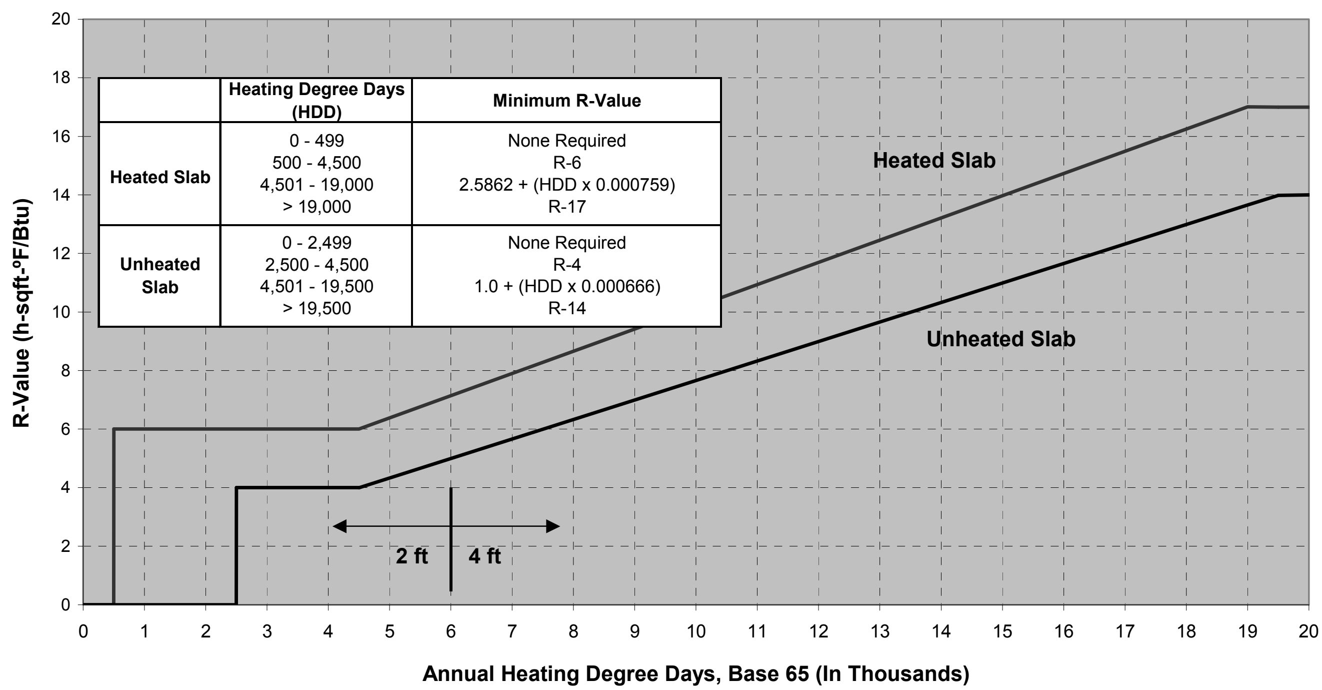


Figure 3. Unvented crawl space wall U-value (excerpted from ICC 2003)



Heating Degree Days (HDD)	Maximum U0-Factor
0 - 1,499	None Required
1,500 - 4,500	0.205 - (HDD x 0.0000233)
4,501 - 8,500	0.11125 - (HDD x 0.0000025)
8,501 - 9,000	0.6 - (HDD x 0.00006)
> 9,000	0.06

Figure 4. Basement wall U-value (excerpted from ICC 2003)



	Heating Degree Days (HDD)	Minimum R-Value
Heated Slab	0 - 499 500 - 4,500 4,501 - 19,000 > 19,000	None Required R-6 2.5862 + (HDD x 0.000759) R-17
Unheated Slab	0 - 2,499 2,500 - 4,500 4,501 - 19,500 > 19,500	None Required R-4 1.0 + (HDD x 0.000666) R-14

Figure 5. Slab insulation R-value and depth (excerpted from ICC 2003)

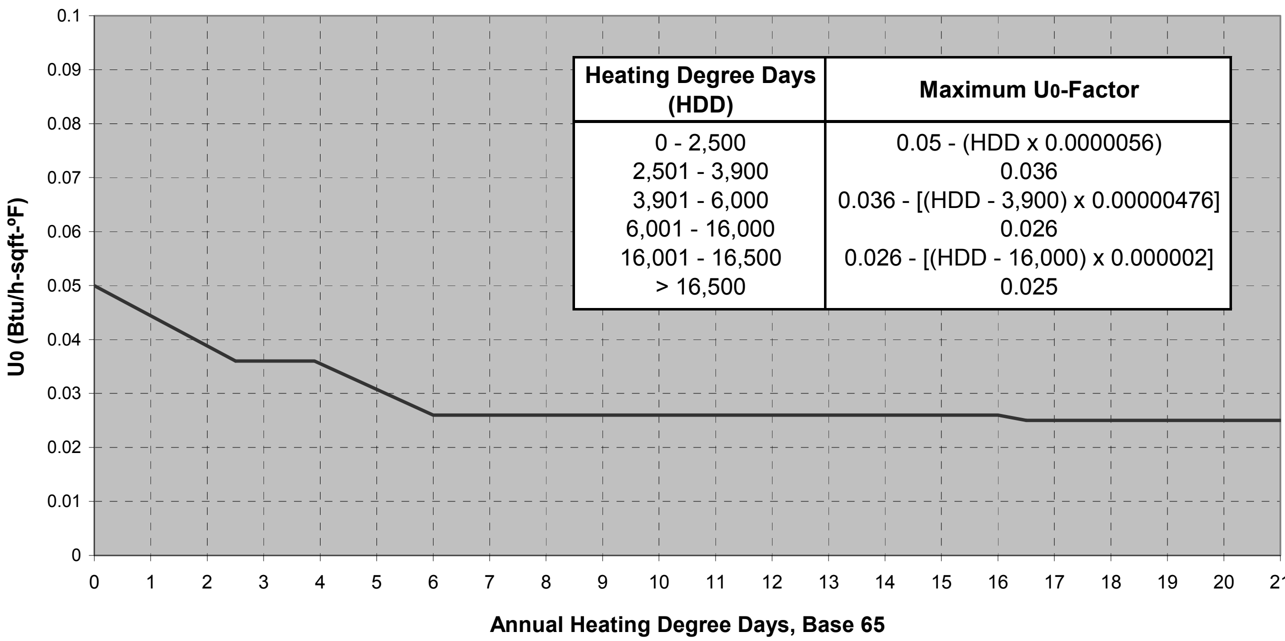


Figure 6. Roof/ceiling assembly U-value (excerpted from ICC 2003)

Table 3. Benchmark Framing Factors

Enclosure Element	Frame Spacing (inches o.c.)	Framing Fraction (% area)
Walls	16	23%
Floors	16	13%
Ceilings below unconditioned space	24	11%

Space Conditioning/Air Distribution Equipment

Space conditioning equipment type and efficiency for the BA Benchmark shall meet the following requirements:

- The minimum National Appliance Energy Conservation Act (NAECA) efficiency in effect on January 1, 1992, for the same type of heating, ventilating, and air-conditioning (HVAC) equipment found in the Rated Home, except that the efficiencies given in Table 4 are assumed when
  - (a) a type of device not covered by NAECA is used in the Prototype
  - (b) the Prototype is heated by electricity using a device other than an air source heat pump
  - (c) the Prototype does not have a heating system, and there is at least one month in which heating is required (see the section on Operating Conditions)
  - (d) the Prototype does not have a cooling system.
- Heating and cooling equipment (including the air handler) shall be sized using the procedures published by the Air Conditioning Contractors of America (ACCA). (www.accaconference.com/Merchant2/merchant.mv?Screen=CTGY&Store_Code=ACCOA&Category_Code=M)
- The Benchmark shall not have a whole-house fan.
- The Benchmark shall have no supplemental dehumidification beyond that provided by a standard air conditioner.
- The Benchmark air handler shall have power consumption equal to 0.00055 kW/cfm.

The air-distribution system in the Benchmark shall have the properties listed in Table 5. The location of the ductwork in the Benchmark is based on the air handler's location in the Prototype. If the simulation tool does not permit the input of duct specifications to this level of detail, then two values (one for heating, one for cooling) of seasonal distribution system efficiency (DSE) shall be estimated and applied to the heating and cooling system efficiencies to represent typical losses from ducts. The DSE values shall be determined using Table 5 and the procedures in the Draft ASHRAE Standard 152P (ASHRAE 2001). A spreadsheet developed by Lawrence Berkeley National Laboratory (LBNL) and modified by NREL is posted on the Building America Web site to assist with this calculation.

Table 4. Benchmark Space Conditioning Equipment Efficiencies

Prototype Equipment	Function	Benchmark Space Conditioning Device
Electric or No System	Heating	6.8 HSPF Air Source Heat Pump
Non-Electric Boiler	Heating	80% AFUE Gas Boiler
Non-Electric Warm Air Furnace or Other Non-Electric Heating	Heating	78% AFUE Gas Furnace
Any Type or No System	Cooling	10 SEER Electric Air Conditioner

Table 5. Duct Locations and Specifications for the Benchmark

	Prototype Air Handler Location[a]	Benchmark Duct Specification	
		One-Story	*Two-Story or Higher*
Supply Duct Surface Area (ft^2)	All	0.27 x FFA[b]	0.20 x FFA
Return Duct Surface Area (ft^2)	All	0.05 x $N_{returns}$ x FFA (Maximum of 0.25 x FFA)	0.04 x $N_{returns}$ x FFA (Maximum of 0.19 x FFA)
Supply Duct Insulation (Conditioned Space)	All	R-3.3	
Return Duct Insulation (Conditioned Space)	All	None	
Supply / Return Duct Insulation (Unconditioned Space)	All	R-5.0	
Duct Material	All	Sheet Metal	
Duct Leakage (Inside + Outside)	All	10% of Air Handler Flow (6.5% Supply, 3.5% Return) Percentage lost to each space equal to percentage of duct area in that space, as specified below	
Supply Duct Location	Attic	100% Attic	65% Attic, 35% Conditioned Space
	Crawl space	95% Crawl space, 5% Exterior Walls	60% Crawl space, 35% Conditioned Space, 5% Exterior Walls
	Basement	95% Basement, 5% Exterior Walls	60% Basement, 35% Conditioned Space, 5% Exterior Walls
	Other Location or Ductless System ≥5000 HDD	95% Basement or attic if Prototype has no basement, 5% Exterior Walls	60% Basement or attic if Prototype has no basement, 35% Conditioned Space, 5% Exterior Walls
	Other Location or Ductless System <5000 HDD	100% Attic	65% Attic, 35% Conditioned Space
Return Duct and Air Handler Location	Attic	100% Attic	100% Attic
	Crawl space	95% Crawl space, 5% Exterior Walls	95% Crawl space, 5% Exterior Walls
	Basement	95% Basement, 5% Exterior Walls	95% Basement, 5% Exterior Walls
	Other Location or Ductless System ≥5000 HDD	95% Basement or attic if Prototype has no basement, 5% Exterior Walls	95% Basement or attic if Prototype has no basement, 5% Exterior Walls
	Other Location or Ductless System <5000 HDD	100% Attic	100% Attic

[a] If the Prototype has more than one air handler, the properties of the Benchmark air distribution system shall be apportioned based on the capacity of each air handler.

[b] Finished floor area.

Domestic Hot Water

The assumptions in Table 6 shall be made for the domestic hot water system in the Benchmark. Both storage and burner capacity are determined using the guidelines recommended by ASHRAE in the *HVAC Applications Handbook* (ASHRAE 1999); these are based on the minimum capacity permitted by the Department of Housing and Urban Development (HUD) and the Federal Housing Administrations (FHA) (HUD 1982). Energy factor is the NAECA minimum for the corresponding fuel type and storage capacity (DOE 2002a). An example set of domestic hot water (DHW) specifications for a typical three-bedroom, two-bathroom Prototype is shown in Table 7. The "Appliance and DHW" spreadsheet developed by NREL automates many of the equations discussed in the following paragraphs and can be downloaded from the Building America Web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html).

Table 6. Characteristics of Benchmark Domestic Hot Water System

	Water Heater Fuel Type in Prototype	
	Electric	*Gas*
Storage Capacity (V) (Gallons)	See *ASHRAE HVAC Applications 1999*	See *ASHRAE HVAC Applications 1999*
Energy Factor (EF)	0.93 – (0.00132 x V)	0.62 – (0.0019 x V)
Recovery Efficiency (RE)	0.98	0.76
Burner Capacity	See *ASHRAE HVAC Applications 1999*	See *ASHRAE HVAC Applications 1999*
Hot Water Set-Point	120°F	
Fuel Type	Same as Prototype[a]	
Tank Location	Same as Prototype	

[a] *If the Prototype does not have a DHW system, or the hot water system uses solar energy or a fuel other than gas or electricity, the Benchmark shall use the same fuel for water heating as that used for space heating.*

Table 7. Example Characteristics of Benchmark Domestic Hot Water System for a Prototype with Three Bedrooms and Two Bathrooms

	Water Heater Fuel Type in Prototype	
	Electric	*Gas*
Storage Capacity (V) (Gallons)	50	40
Energy Factor (EF)	0.86	0.54
Recovery Efficiency (RE)	0.98	0.76
Burner Capacity	5.5 kW	36,000 Btu/hr
Supply Temperature	120°F	
Fuel Type	Same as Prototype	
Tank Location	Same as Prototype	

NREL has also developed a spreadsheet that calculates the correct DHW inputs for the TRNSYS computer program, including standby heat loss coefficient (UA). The spreadsheet also has a comprehensive set of inputs and outputs that can be used to help calculate DHW properties for the Prototype house (Burch 2004). It can be found on the Building America Web site in the section for building scientists (http://www.eere.energy.gov/buildings/building_america/pa_resources.html).

Four major end uses are identified for domestic hot water: showers, sinks, dishwasher, and clothes washer. The average daily water consumption by end use is shown in Table 8. The specified volume is the combined hot and cold water for showers and sinks, which allows hot water use to fluctuate, depending on the cold water (mains) temperature.[2] Hot water usage for the clothes washer and dishwasher is derived from the EnergyGuide labels for the least efficient of several common models sampled by NREL. For showers and sinks, the water usage is based on the average of four domestic hot water studies (Christensen 2000, Burch 2002, ASHRAE 1999, and CEC 2002). The relationship between the number of bedrooms and hot water usage was derived from the 1997 Residential Energy Consumption Study (RECS) (DOE 1999). This relationship also applies to machine energy for certain appliances.

[2] The clothes washer in the Prototype may also consume a variable amount of hot water depending on mains temperature if it uses a thermostatic control valve to adjust the proportion of hot and cold water necessary to maintain a certain wash temperature. However, the Benchmark clothes washer does not have this feature.

Table 8. Domestic Hot Water Consumption by End Use

End Use	End-Use Water Temperature	Water Usage
Clothes Washer	N/A	7.5 + 2.5 x N_{br} gal/day (Hot Only)
Dishwasher	N/A	2.5 + 0.833 x N_{br} gal/day (Hot Only)
Shower and Bath	105°F	14 + 4.67 x N_{br} gal/day (Hot + Cold)
Sinks	105°F	10 + 3.33 x N_{br} gal/day (Hot + Cold)

The typical ASHRAE hot water use profile (Figure 7) is adequate for analyzing most applications (ASHRAE 1999). NREL is currently investigating profiles for individual hot water end uses. In the meantime, the ASHRAE profile shall be used for each hot-water-consuming appliance, as well as sinks and showers.

The mains water temperature for a typical house varies significantly depending on the location and time of year. The following equation, based on TMY2 data for the location of the Prototype, shall be used to determine the daily mains water temperature for both the Benchmark and the Prototype:

Equation 5: $$T_{mains} = (T_{amb,avg} + \textit{offset}) + \textit{ratio} * (\Delta T_{amb,max} / 2) * \sin(0.986 * (\text{day\#} - 15 - \textit{lag}) - 90)$$

where

T_{mains}	=	mains (supply) temperature to domestic hot water tank
$T_{amb,avg}$	=	annual average ambient air temperature
$\Delta T_{amb,max}$	=	maximum difference between monthly average ambient temperatures (e.g., $T_{amb,avg,july} - T_{amb,avg,january}$)
0.986	=	degrees/day (360/365)
day#	=	Julian day of the year (1-365)
offset	=	6°F
ratio	=	$0.4 + 0.01 (T_{amb,avg} - 44)$
lag	=	$35 - 1.0 (T_{amb,avg} - 44)$.

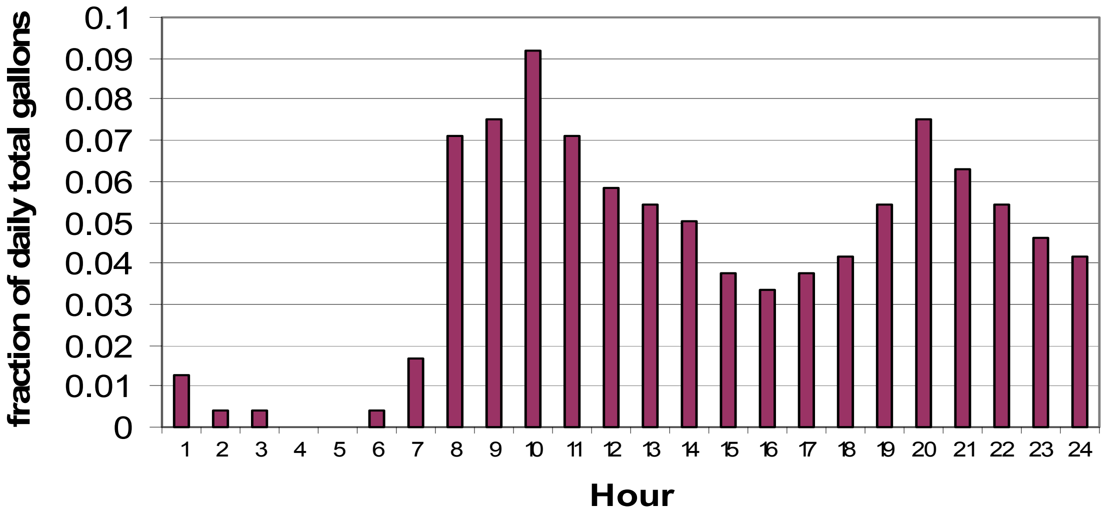


Figure 7. ASHRAE hot water use profile (Source: ASHRAE 1999)

This equation is based on analysis by Christensen and Burch of NREL using data for multiple locations, as compiled by Abrams and Shedd (Abrams 1996), Florida Solar Energy Center (Parker 2002), and Sandia National Laboratories (Kolb 2003). The *offset, ratio,* and *lag* factors were determined by fitting the available data. The climate-specific *ratio* and *lag* factors are consistent with water pipes being buried deeper in colder climates.

In order for the constant terms in the *ratio* and *lag* factors to be representative of an average climate, the data fitting was done relative to a nominal $T_{amb,avg}$ = 44ºF. The *lag* is relative to ambient air temperature, and $T_{amb,minimum}$ is assumed to occur in mid-January (day# = 15). The choices for these nominal values are not critical, because although different assumptions would change the constant terms in the *ratio* and *lag* factors, the coefficients would also change, so the prediction of T_{mains} values would be unchanged. For models that use average monthly mains temperature, day# in Equation 5 shall be calculated using Equation 6.

Equation 6: day# = 30 * month# - 15

where

month# = month of the year (1–12).

An example of using Equations 5 and 6 to determine the monthly mains temperature profile for Chicago, Illinois, is shown in Figure 8.

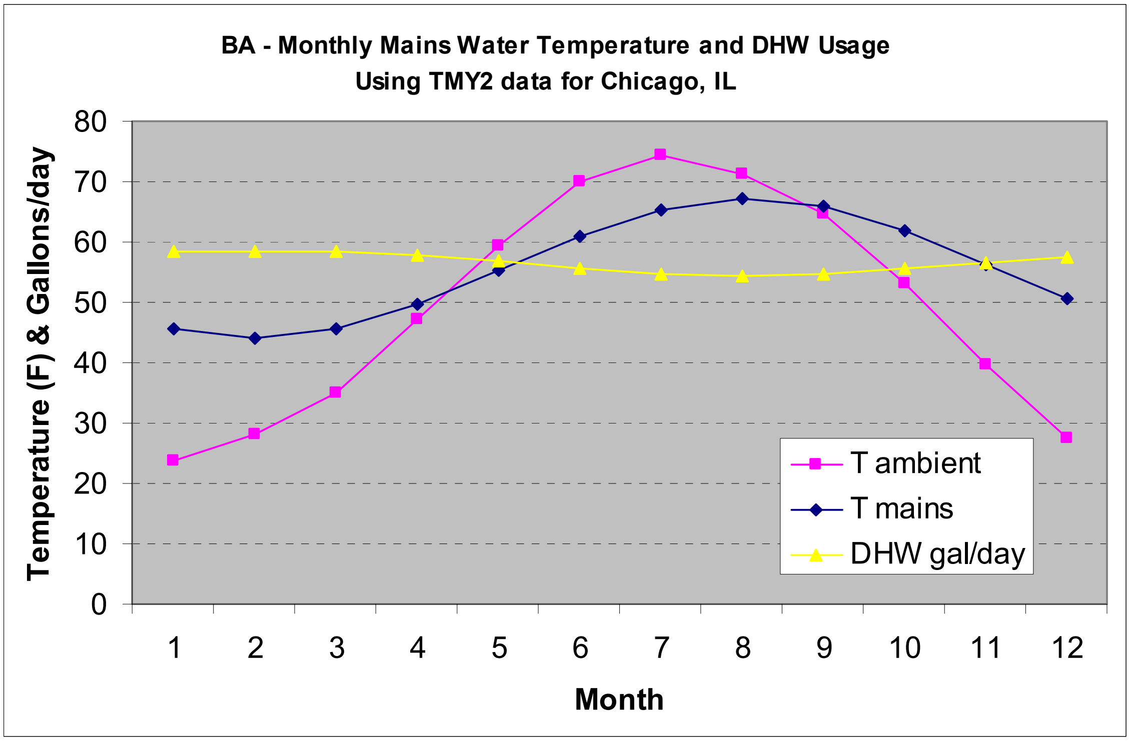


Figure 8. Mains temperature profile for Chicago

Air Infiltration and Ventilation

The natural air change rate for the Benchmark shall be based on the annual average ACH determined using Equation 7:

$$\textbf{Equation 7:} \quad ACH = L_n \times W \times F_B$$

where

ACH = (volumetric rate at which outside air enters the home) / (building volume including all directly or indirectly conditioned basements and crawl spaces)

L_n = normalized leakage = 0.75 [3]

W = Weather factor from W tables in ASHRAE Standard 136-1993 for the site most representative of the climate at the Prototype's location

F_B = (exposed thermal boundary surface area)/(total thermal boundary surface area),

[3] The normalized leakage for the Benchmark has been increased from 0.57 (specified in the HERS 1999 guidelines) to 0.75 to compensate for the use of the term F_B, which ranges from 0 to 1 and adjusts ACH based on the fraction of thermal envelope area that is exposed to the outside (therefore contributing to the effective leakage area). The increased normalized leakage results in a typical slab-on-grade Prototype having the same annual average ACH as the Reference Home in HERS 99. Vented crawl spaces would result in higher ACH, while conditioned basements would have a lower ACH.

and where

total thermal boundary surface area is the area of all surfaces that separate directly or indirectly conditioned space from unconditioned space or ambient conditions, including the walls and floors of unvented crawl spaces and directly or indirectly conditioned basements.

exposed thermal boundary surface area is the area of all thermal boundary surfaces not in contact with soil. An exception is the area of floors over unconditioned basements, which shall not be considered exposed in calculating F_B.

If the simulation tool is capable of calculating hourly air infiltration, an Effective Leakage Area or other input may be specified, as long as the annual average ACH is approximately equal to the value calculated above. No additional air exchange resulting from mechanical ventilation shall be assumed for the Benchmark.

An alternative approach for specifying natural infiltration for a Benchmark with a directly or indirectly conditioned basement is to adjust the Specific Leakage Area (SLA) to account for the in-ground portions of the walls of the conditioned basement. Equation 8 can be used to do this.

Equation 8: $$\mathbf{SLA_{overall} = [(CFA_{bsmt} * SLA_{bsmt}) + (CFA_{a\text{-}g} * SLA_{a\text{-}g})] / [CFA_{total}]}$$

where

SLA	=	effective leakage area (ft^2) / CFA (ft^2)
$SLA_{a\text{-}g}$	=	SLA_{std} (where subscript "a-g" indicates above-grade or exposed)
SLA_{bsmt}	=	SLA_{std}*(above-grade basement wall area)/(total basement wall area)
SLA_{std}	=	0.00057
CFA	=	conditioned floor area.

This can be calculated by zone, applying SLA_{bsmt} to the basement zone and SLA_{std} to the above-grade zone of the Benchmark and treating the energy balances separately for each zone. It could also be done by applying $SLA_{overall}$ to the combined spaces if the Benchmark is modeled as a single zone.

Fan energy use for the Benchmark shall be calculated using Equation 9.

Equation 9: $$\textbf{Ventilation fan energy (kWh/yr)} = \mathbf{0.03942 \times FFA + 29.565 \times (N_{br} + 1)}$$

where

FFA	=	finished floor area (ft^2)
N_{br}	=	number of bedrooms.

Note that finished floor area is used in this equation instead of conditioned floor area. We believe that finished floor area more accurately represents the area that occupants use in their daily activities (see also the treatment of lighting and plug loads).

Cross-ventilation is available to provide natural ventilation in the Benchmark under favorable weather conditions.

Lighting Equipment and Usage

The total annual lighting use for the Benchmark is determined using Equations 10-12. These equations are derived from data for both single-family and multi-family housing documented in a lighting study conducted by Navigant for DOE (Navigant 2002).

Equation 10: Interior lighting = (FFA * 0.8 + 455) kWh/yr

Equation 11: Garage lighting = 100 kWh/yr

Equation 12: Exterior lighting = 250 kWh/yr

Annual indoor lighting, in kilowatt-hours, is expressed as a linear function of finished house area relative to a constant base value, while garage and exterior lighting are constants. This equation is in the middle range of residential lighting energy use found in other lighting references, as shown in Figure 9, including Huang and Gu (2002), the 1993 RECS (DOE 1996), a Florida Solar Energy Center study (Parker 2000), default lighting for Visual DOE software (Eley 2002), a lighting study conducted by Navigant for DOE (Navigant 2002), and two other studies in Grays Harbor, Washington (Manclark and Nelson 1992), and Southern California (SCE 1993).

The Benchmark lighting budget is based on an assumption that 90% of the interior lighting comes from fixtures that contain incandescent lamps, and the remaining 10% is assumed to come from fixtures containing fluorescent lamps. This is consistent with the source data set from 161 homes monitored by Tacoma Public Utilities (TPU) for the Bonneville Power Administration, which was the basis for the Navigant study. Although the core data set used in this study is the most complete and comprehensive residential lighting data set that we have identified, it is nevertheless limited in terms of geographic location, number of homes, length of study, percent of fixtures monitored, and type of homes studied. The Navigant report includes an appendix providing information about the characteristics of the homes monitored in the TPU study.

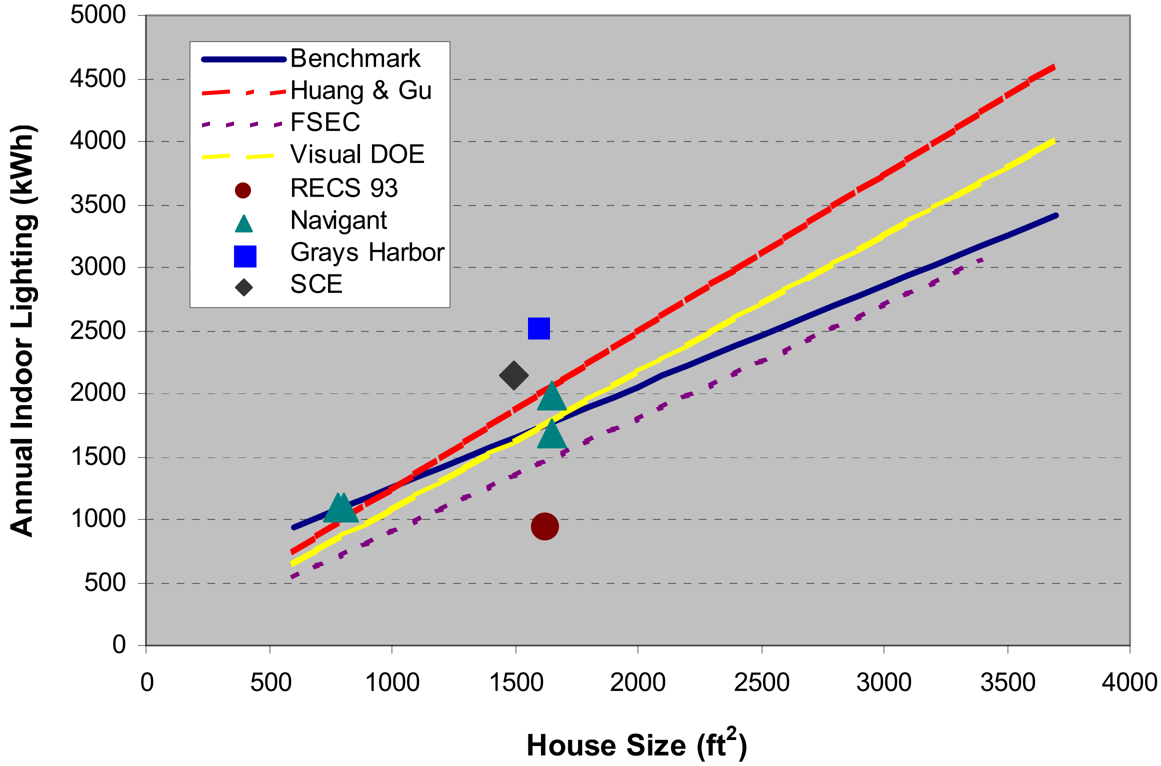


Figure 9. Comparison of Benchmark lighting equation to other references

The annual average normalized daily load shape for interior lighting use is shown in Figure 10, based on a draft LBNL report by Huang and Gu (2002). This load shape is also used for exterior and garage lighting. Monthly variations in load shape and lighting energy use due to changes in the length of days can be accounted for, as long as the variation is applied to all the simulation models and total annual energy use remains the same.

Energy savings may be calculated on the basis of a number of usage variations, depending on the capability of the modeling tool. Variations include day types (weekday vs. weekend), occupancy types (day-use vs. non-day-use or "nuclear" vs. "yuppie"), season (summer vs. winter), and room types (living area vs. bedroom area).

Individual normalized profiles can be "rolled up" to various levels of detail appropriate to the simulation model. An example of one detailed set of profiles developed by NREL is shown in Figure 11. Other profiles are included in spreadsheets available on the Building America Web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html).

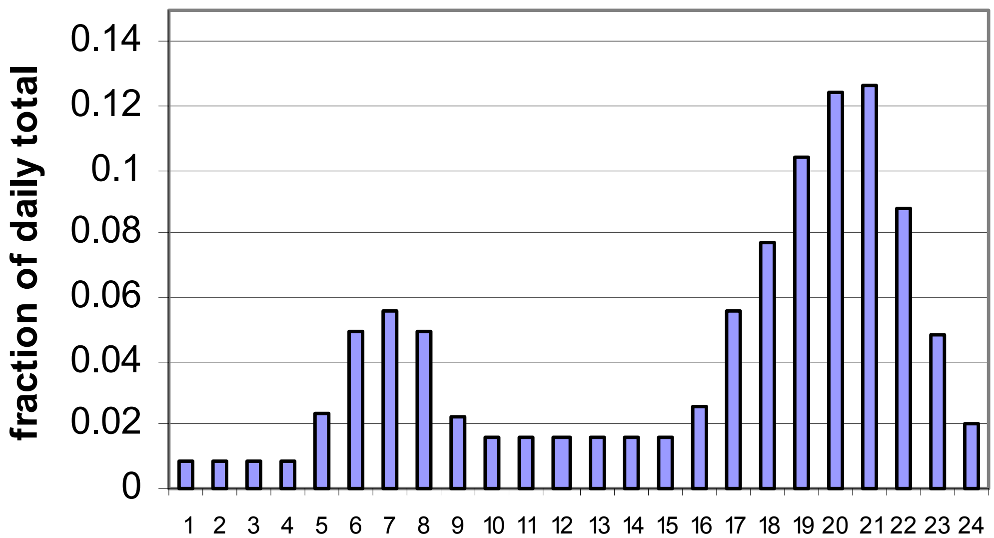


Figure 10. Interior lighting profile (Built up from detailed profiles)

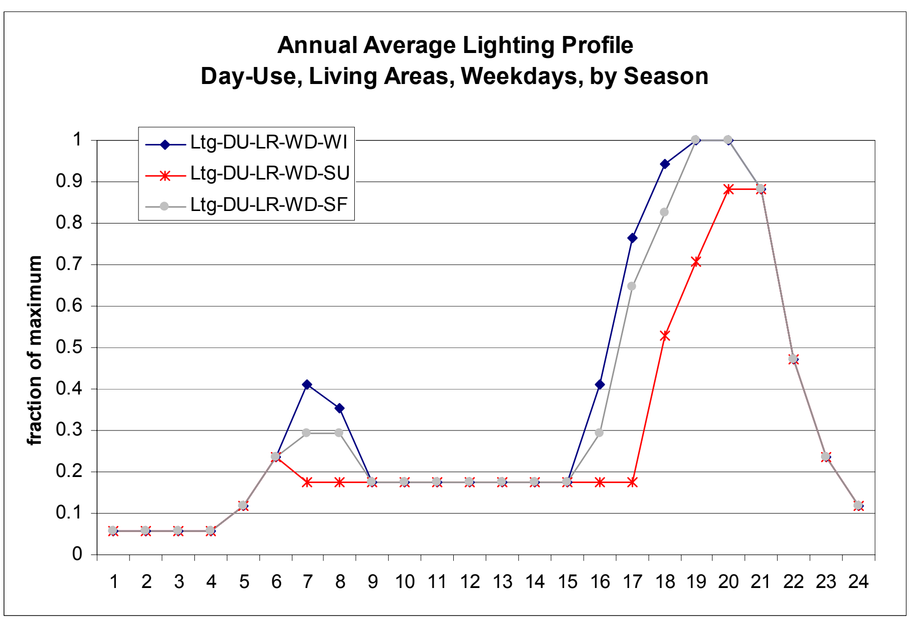


Figure 11. Example of a detailed lighting profile (expressed as fraction of peak daily lighting energy)

Table 9. Average Lighting Operating Hours for Common Room Types in a Sample of 161 Homes in the Pacific Northwest (Source: Navigant 2002)

Room Type	Operation (Hours/day/room)	Room Type	Operation (Hours/day/room)
Bathroom	1.8	Kitchen	3.0
Bedroom	1.1	Living Room	2.5
Closet	1.1	Office	1.7
Dining Room	2.5	Outdoor	2.1
Family Room	1.8	Utility Room	2.0
Garage	1.5	Other	0.8
Hall	1.5		

The lighting plans for the Prototype and Benchmark should be based on the same hours of operation unless the Prototype includes specific design measures that alter the operating time of the lighting system, such as occupancy sensors, dimming switches, or a building automation system. Average operating hours estimated in the Navigant study are generally a good starting point (Table 9), but there may be substantial differences between typical lighting designs found in the TPU sample and the lighting design developed in conjunction with the architecture of the Prototype. The analyst must ultimately apply good engineering judgment when specifying operating hours for the lighting system.

Appliances and Other Plug Loads

As with lighting, several characteristics must be defined for appliances and other plug loads: the amount of the load, the schedule of the load, the location of the load, the fraction of the load that becomes a sensible load, and the fraction of the load that becomes a latent load. Though the internal load may be treated as an aggregate, the energy consumption for each end use must be considered separately. A breakdown of annual energy consumption and associated internal loads for major appliances and other equipment is shown in Table 10. Not all of the energy consumed by appliances is converted into internal load; much of the waste heat is exhausted to the outside or released down the drain in the form of hot water. The appliance loads were derived by NREL from EnergyGuide labels and from a Navigant analysis of typical models available on the market that meet current NAECA appliance standards. The daily loads rolled up at the whole-house level for a typical 1800-ft^2, three-bedroom house are shown in Table 11.

For a house of typical size (1000-3000 ft^2), the loads from the occupants and most appliances are assumed to be a function of the number of bedrooms. The exceptions are the refrigerator and cooking loads, which are assumed to be constant regardless of the number of bedrooms. The "Other Appliance & Plug Loads" end use is assumed to be a function of finished floor area. This function brings the total internal sensible load (including heat gain from occupants) approximately in line with the equation used to calculate internal loads in the IECC (ICC 2003). Note, however, that the internal load from appliances and lighting in the IECC equation is not a function of the number of bedrooms. Therefore, it is impossible to fully reconcile the Benchmark internal heat gain with that of the IECC for all combinations of floor area and number of bedrooms. However, the internal loads for the Benchmark and IECC are consistent for a typical 1800-ft^2, three-bedroom house.

The constant internal sensible load value of 72,000 Btu/day specified in the HERS guidelines (RESNET 1999) is even less flexible than the equation in the IECC. Still, the HERS internal load is approximately the same as the sensible load calculated using Table 10 (73,052 Btu/day) for a typical 1800-ft^2, three-bedroom house. Table 10 also results in a total latent load equal to approximately 20% of the total sensible load for a house of typical size, which is consistent with the HERS Guidelines. The IECC does not address latent load.

Table 10. Annual Appliance and Equipment Loads for the Benchmark[4]

Appliance	Electricity (kWh/yr)	Natural Gas (therms/yr)	Sensible Load Fraction	Latent Load Fraction
Refrigerator	669		1.00	0.00
Clothes Washer (3 ft^3 drum)	$52.5 + 17.5 \times N_{br}$		0.80	0.00
Clothes Dryer (Electric)	$418 + 139 \times N_{br}$		0.15	0.05
Clothes Dryer (Gas)	$38 + 12.7 \times N_{br}$	$36 + 12.0 \times N_{br}$	1.00 (Electric) 0.10 (Gas)	0.00 (Electric) 0.05 (Gas)
Dishwasher (8 place settings)	$103 + 34.3 \times N_{br}$		0.60	0.15
Range (Electric)	604		0.40	0.30
Range (Gas)		78	0.30	0.20
Other Appliance & Plug Loads	1.67 x FFA		0.90	0.10

Table 11. Total Rolled-Up Appliance and Equipment Loads for the Benchmark (1800-ft^2, three-bedroom prototype)

House Type	Electricity (kWh/yr)	Sensible Fraction	Latent Fraction	Nat. Gas (therms/yr)	Sensible Fraction	Latent Fraction
All Electric	5425	0.75	0.10			
Elec w/gas dryer	4666	0.85	0.11	72	0.10	0.05
Elec w/gas cooking	4821	0.79	0.08	78	0.30	0.20
Gas dryer/cooking	4062	0.92	0.08	150	0.20	0.13

[4] End-use loads in this table include only energy used within the machine. Associated domestic hot water use is treated separately (see "Domestic Hot Water"). The Appliance spreadsheet on the Building America Web site (www.eere.energy.gov/buildings/building_america/benchmark_def.html) can assist with the calculation of this split for an energy-efficient clothes washer or dishwasher based on the EnergyGuide label.

The hourly normalized load shape for interior residential equipment use is shown in Figure 12 (Huang and Gu 2002). The equipment profile is the sum of individual profiles of each piece of equipment; some individual profiles are nearly constant (such as refrigerator and transformer loads), and some are highly dependent on time of day (such as the range and dishwasher). NREL is in the process of developing hourly profiles for individual appliances. In the meantime, the equipment profile in Figure 12 can be used for either individual appliances or equipment in the aggregate. Internal sensible and latent loads from equipment should also be modeled using this profile. Appliance loads may be modeled in either the living spaces or bedroom spaces, depending on their location in the Prototype.

Large end uses in the Prototype that are not part of typical houses (such as swimming pools, Jacuzzis, and workshops) are not included in the models for either the Prototype or the Benchmark. The efficiency of these end uses should be addressed in a separate analysis.

Site Generation

A review of data from the Energy Information Administration (DOE 2001a) shows that there is rarely any site electricity generation in a 1990s vintage house. This is a reflection of the low market penetration of site electricity systems. Therefore, all electricity is purchased from the local utility in the Benchmark. As costs for photovoltaic systems and other site electricity systems continue to decline, they are expected to begin to make a significant contribution toward meeting residential energy needs by the year 2020. Therefore, it is important that site electricity generation must be included in the whole-house energy performance of the prototype.

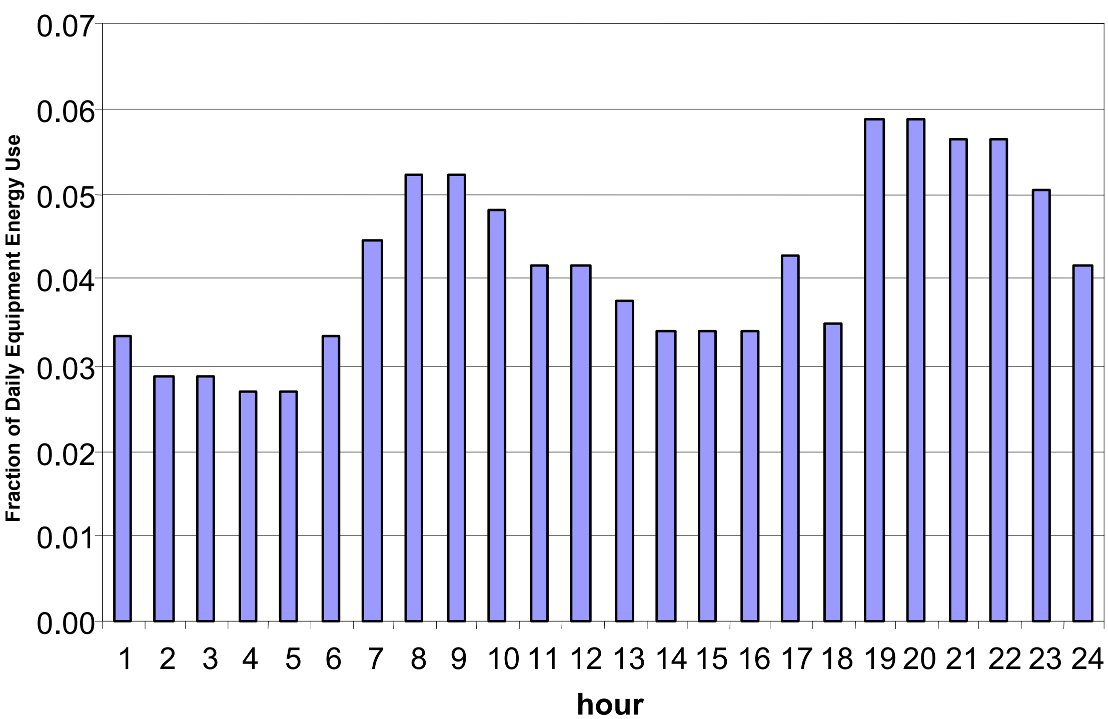


Figure 12. Interior residential equipment profile

Operating Conditions

The following operating conditions and other assumptions shall apply to both the Prototype house and the Benchmark. The operating conditions are based on the cumulative experience of the authors through their work on Building America, HERS, Codes and Standards, and other residential energy efficiency programs.

- Thermostat set point for cooling: 78°F with no setup period
- Thermostat set point for heating: 68°F with no setback period
- The natural ventilation schedule shall be set to reflect windows being opened occasionally. In situations in which there is a cooling load, the outdoor temperature is below the indoor temperature, and the window is not already open, then the probability of the window being opened shall be set at a constant 50%. For tools that do not have the capability to calculate air infiltration effects caused by window openings, natural ventilation rates shall be set at 5 ACH unless each living area and bedroom provides at least two openings on different orientations and the net area of openings exceeds 12% of the floor area of the house (cross-ventilation), in which case a natural ventilation rate of 7 ACH shall be used.
- Interior shading multiplier = 0.7 during the cooling season and 0.85 during the heating season and during swing seasons when both cooling and heating occur. Specific guidelines for defining seasons are presented later in this section.
- Internal loads from lighting, appliances, and other equipment were discussed in previous sections. These loads are not necessarily the same for the Prototype and the Benchmark; therefore, they are not considered operating conditions for the purposes of the Building America performance analysis.
- The occupancy schedule is defined with the same level of detail as other internal load profiles. For typical Building America houses, the number of occupants shall be assumed to be equal to the number of bedrooms. Sensible and latent gains shall be accounted for separately, and different loads shall be applied in different space types, as described in Table 12. The occupant heat gains are based on ASHRAE recommendations (ASHRAE 2001). The average hourly occupancy profile is shown in Figure 13, and an example set of detailed hourly occupancy curves is shown in Figure 14. For detailed occupancy profiles for various day types, see the Building America Web site (http://www.eere.energy.gov/buildings/building_america/pa_resources.html). These profiles, which were developed by NREL, were based on the basic ASHRAE occupancy schedule combined with engineering judgment.

Table 12. Peak Sensible and Latent Heat Gain from Occupants (ASHRAE 2001)

Living Area Sensible Gain:	230	BTU/person/hr
Bedroom Area Sensible Gain:	210	BTU/person/hr
Living Area Latent Gain:	190	BTU/person/hr
Bedroom Area Latent Gain:	140	BTU/person/hr

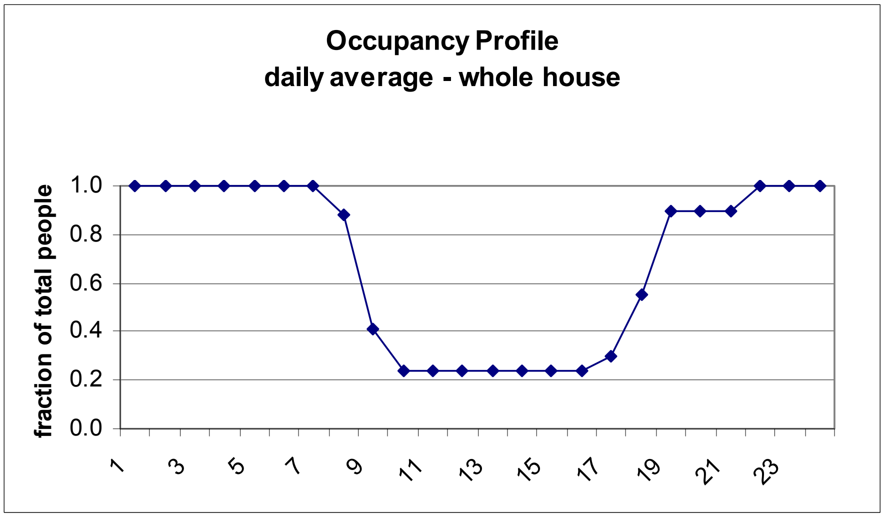


Figure 13. Average hourly load profile from occupants for all day-types and family types (16.5 hours/day/person total)

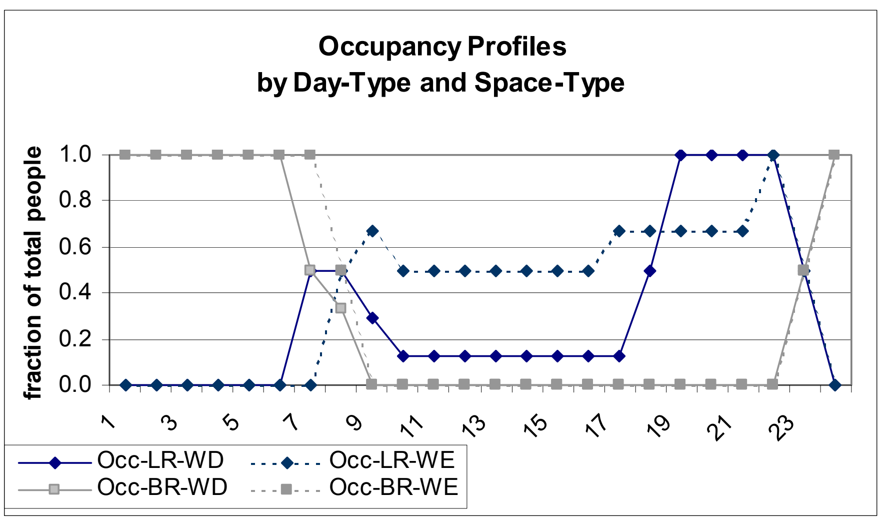


Figure 14. Detailed hourly load profiles resulting from occupants being in different parts of the house on weekdays (WD) and weekends (WE)

- The internal mass of furniture and contents shall be equal to 8 lbs/ft^2 of conditioned floor space. For solar distribution purposes, lightweight furniture covering 40% of the floor area shall be assumed.

- Weather data shall be based on typical meteorological year (TMY2) data from 1961–1990[5] or equivalent data for the nearest weather station.

- Heating and cooling shall occur only during certain months of the year in accordance with the following guidelines developed by the Florida Solar Energy Center (FSEC). These guidelines serve as the basis for defining seasons in the EnergyGauge software. Alternate operating profiles may be acceptable with sufficient justification.

- The heating and cooling seasons shall be determined on the basis of the monthly average temperatures (MAT) and the 99% (annual, not seasonal) winter and summer design temperatures (WDT and SDT, respectively) based on TMY2 data or ASHRAE Fundamentals 2001 for the nearest location, in accordance with the following procedures:

  Step 1. MAT Basis

  (I) The heating system shall be enabled for a month in which the MAT is less than 71.5°F.

  (II) The cooling system enabled for a month in which the MAT is greater than 66°F.

  Step 2. WDT and SDT

  (I) The heating system shall be enabled in December and January if the WDT is less than or equal to 59°F, regardless of the outcome in Step 1 above.

  (II) The cooling system shall be enabled in July and August regardless of the outcome in Step 1 above.

  Step 3. Swing Season Adjustment

  (I) If, based on Steps 1 and 2 above, there are two consecutive months in which the heating system is enabled the first month and the cooling system is enabled the following month, or vice versa, then both the heating system and the cooling system shall be enabled for both these months.

Reporting Energy Use and Energy Savings

Reporting energy use and energy savings in a consistent format is an important component of Building America analysis. The following tables shall be supplied with the analysis report for every Building America Prototype. The Benchmark version number should be identified in the caption to ensure that the results are interpreted in the correct context and not compared with results obtained using a different version of the Benchmark.

Table 13 shows an example of a site energy consumption report for a hypothetical Prototype in Virginia, along with all relevant base cases. Similar information based on source energy is

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[5] Analytic Studies Division, National Renewable Energy Laboratory (http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/).

presented energy in Table 14, along with percent energy savings for each end use. End uses are described in more detail in Table 15.

The "Percent of End Use" columns in Table 14 show the Prototype energy use for each end use as a fraction of the appropriate base case. The "Percent of Total" columns show the contribution of each end use toward an overall energy reduction goal. Note that site generation for the Benchmark is always zero.

Source energy is determined using Equation 17.

$$\textbf{Equation 17:}\quad \textbf{Source MBtu} = \textbf{kWh} \bullet \textbf{3.412} \bullet \textbf{M}_e \textbf{/1000} + \textbf{therms} \bullet \textbf{M}_g \textbf{/ 10}$$

where

M_e = 3.16 = site to source multiplier for electricity (DOE 2002b)

M_g = 1.02 = site to source multiplier for natural gas (DOE 1995).

Table 13. Example Summary of Site Energy Consumption by End Use Using Building America Research Benchmark Version 3.1

	Annual Site Energy							
	BA Benchmark		Region Standard		Builder Standard		BA Prototype	
End Use	(kWh)	(therms)	(kWh)	(therms)	(kWh)	(therms)	(kWh)	(therms)
Space Heating	11225	0	11286	0	11286	0	4397	0
Space Cooling	2732	0	2432	0	2432	0	902	0
DHW	4837	0	4838	0	4838	0	1351	0
Lighting	3110		3110		3110		1204	
Appliances + Plug	7646	0	7646	0	7646	0	7436	0
OA Ventilation	400		400		400		400	
Total Usage	29950	0	29712	0	29712	0	15690	0
Site Generation	0	0	0	0	0	0	7402	0
Net Energy Use	29950	0	29712	0	29712	0	8289	0

Table 14. Example Summary of Source Energy Consumption by End Use Using Building America Research Benchmark Version 3.1

	Estimated Annual Source Energy				Source Energy Savings					
					Percent of End-Use			Percent of Total		
End Use	Benchmark (MBtu/yr)	Region (MBtu/yr)	Builder (MBtu/yr)	Proto (MBtu/yr)	BA Base	Reg Base	Bldr Base	BA Base	Reg Base	Bldr Base
Space Heating	115	116	116	45	61%	61%	61%	23%	23%	23%
Space Cooling	28	25	25	9	67%	63%	63%	6%	5%	5%
DHW	50	50	50	14	72%	72%	72%	12%	12%	12%
Lighting	32	32	32	12	61%	61%	61%	6%	6%	6%
Appliances + Plug	78	78	78	76	3%	3%	3%	1%	1%	1%
OA Ventilation	4	4	4	4	0%	0%	0%	0%	0%	0%
Total Usage	307	304	304	161	48%	47%	47%	48%	47%	47%
Site Generation	0	0	0	-76				25%	25%	25%
Net Energy Use	307	304	304	85	72%	72%	72%	72%	72%	72%

Table 15. End-Use Categories

End Use	Potential Electric Usage	Potential Gas Usage
Space Heating	Supply fan during space heating, HP, HP supplemental heat, water boiler heating elements, water boiler circulation pump, electric resistance heating, HP crankcase heat, heating system auxiliary	Gas furnace, gas boiler, gas back-up HP supplemental heat, gas ignition stand-by
Space Cooling	Central split-system A/C, packaged A/C (window or through-the-wall), supply fan energy during space cooling, A/C crankcase heat, cooling system auxiliary	Gas absorption chiller (rare)
DHW	Electric hot water heater, HP water heater, hot water circulation pumps	Gas hot water heater
Lighting	Indoor lighting, outdoor lighting	None
Equipment	Refrigerator, electric clothes dryer, gas clothes dryer (motor), cooking, miscellaneous	Cooking, gas clothes dryer
OA Ventilation	Ventilation fans, supply air fan during ventilation mode	None
Site Generation	Photovoltaic electric generation	None

Table 16 reports energy savings for individual energy efficiency measures applied to the Prototype, in terms of source energy and energy cost. "Source Energy Savings %" is determined by comparing the source energy for each measure increment to the source energy for the Benchmark (i.e., the first row). In this column, the incremental savings for each measure are added to the savings for all the previous measures. The final row of the column is the overall energy savings achieved for the Prototype house.

When available, actual energy tariffs for the Prototype house shall be used to determine whole-building energy costs. Energy cost and measure savings are compared with the Builder Standard Practice (representing a real design or set of practices that is currently being used by the builder) rather than with the Benchmark. This provides an evaluation of the improvements in the performance of the Prototype compared with that of homes currently being sold by the builder partner.

Peak hourly energy consumption should also be reported for every Prototype. Peak energy is based on the hour with the greatest gas or electric energy consumption during the course of one year, as determined by the hourly simulation.

Table 16. Example Measure Savings Report[6] Using Building America Research Benchmark Version 3.1

	Site Energy		Est. Source Energy		National Average Energy Cost		Builder Standard (Local Costs) Energy Cost		Builder Standard (Local Costs) Measure	Builder Standard (Local Costs) Package
Increment	(kWh)	(therms)	(MBtu)	Savings (%)	($/yr)	Savings (%)	($/yr)	Savings (%)	Value ($/yr)	Savings ($/yr)
Building America Research Benchmark	29950	0	306.9		$ 2,995		$ 2,950			
Regional Standard Practice	29712	0	304.4	1%	$ 2,971	1%	$ 2,927			
Builder Standard Practice (BSP)	29712	0	304.4	1%	$ 2,971	1%	$ 2,927			
BSP + improved walls	27779	0	284.6	7%	$ 2,778	7%	$ 2,736	7%	$ 190.4	$ 190
BSP ++ Low-E Windows	25810	0	264.5	14%	$ 2,581	14%	$ 2,542	13%	$ 193.9	$ 384
BSP ++ Smaller A/C (5 -> 4 tons)	25420	0	260.5	15%	$ 2,542	15%	$ 2,504	14%	$ 38.4	$ 423
BSP ++ Including Basement Wall Insulation	25170	0	257.9	16%	$ 2,517	16%	$ 2,479	15%	$ 24.6	$ 447
BSP ++ Ground Source HP (+DHW)	19331	0	198.1	35%	$ 1,933	35%	$ 1,904	35%	$ 575.1	$ 1,023
BSP ++ Solar DHW	17718	0	181.5	41%	$ 1,772	41%	$ 1,745	40%	$ 158.9	$ 1,181
BSP ++ Lighting, Appliance & Plug	15690	0	160.8	48%	$ 1,569	48%	$ 1,545	47%	$ 199.8	$ 1,381
Site Generation										
BSP ++ PV	8288	0	84.9	72%	$ 829		$ 816	72%	$ 729.0	$ 2,110

[6] Calculated using national average electric cost = $0.10/kWh and national average gas cost = $0.50/therm.

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14. ABSTRACT *(Maximum 200 Words)*
To track progress toward aggressive multi-year whole-house energy savings goals of 40-70% and onsite power production of up to 30%, the U.S. Department of Energy (DOE) Residential Buildings Program and the National Renewable Energy Laboratory (NREL) developed the Building America Research Benchmark in consultation with the Building America industry teams. The Benchmark is generally consistent with mid-1990s standard practice, as reflected in the Home Energy Rating System (HERS) Technical Guidelines (RESNET 2002), with additional definitions that allow the analyst to evaluate all residential end-uses, an extension of the traditional HERS rating approach that focuses on space conditioning and hot water. A series of user profiles, intended to represent the behavior of a "standard" set of occupants, was created for use in conjunction with the Benchmark.

15. SUBJECT TERMS
Building America; U.S. Department of Energy; residential homes; research benchmark; whole-house energy savings; HERS guidelines

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A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

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Our nation's buildings consume more energy than any other sector of the U.S. economy, including transportation and industry. Fortunately, the opportunities to reduce building energy use—and the associated environmental impacts—are significant.

DOE's Building Technologies Program works to improve the energy efficiency of our nation's buildings through innovative new technologies and better building practices. The program focuses on two key areas:

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  Research and development of the next generation of energy-efficient components, materials, and equipment
- **Technology Integration**
  Integration of new technologies with innovative building methods to optimize building performance and savings

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